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# Combined diversity and improved energy detection in cooperative spectrum sensing with faded reporting channels

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**Abstract** In this paper we evaluate the performance of cooperative spectrum sensing (CSS) where each cognitive radio (CR) employs an improved energy detector (IED) with multiple antennas and uses selection combining (SC) for detecting the primary user (PU) in noisy and faded sensing (S) channels. We derive an expression for the probability of false alarm and expressions for probability of missed detection in non-faded (AWGN) and Rayleigh faded sensing environments in terms of cumulative distribution function (CDF). Each CR transmits its decision about PU via noisy and faded reporting (R) channel to fusion center (FC). In this paper we assume that S-channels are noisy and Rayleigh faded while several cases of fading are considered for R-channels such as: (i) Hoyt (or Nakagami-*q*), (ii) Rayleigh, (iii) Rician (or Nakagami-*n*), and (iv) Weibull. A Binary Symmetric channel (BSC) with a fixed error probability (*r*) in the R-channel is also considered. The impact of fading in R-channel, S-channel and several network parameters such as IED parameter, normalized detection threshold, number of CRs, and number of antennas on missed detection and total error probability is assessed. The effects of Hoyt, Rician, and Weibull fading parameters on overall performance of IED-CSS are also highlighted.


## 1. Introduction

Cognitive radio (CR)[1] is a kind of intelligent wireless device, which is able to adjust its transmission parameters, such as transmit power and transmission frequency band, based on the environment (Haykin, 2005). In a CR network, ordinary wireless devices are referred to as primary users (PUs), and CRs are referred to as secondary users (SUs). The CR user

[1] Note that with the generic term cognitive radio (CR) we also refer to a secondary (or cognitive) user (SU). The context will eliminate any ambiguity.

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can use spectrum only when it does not cause interference to the PUs. Thus sensing of vacant spectrum is very important for a successful operation of CR network. However, sensing the spectrum is a hard task because of shadowing, fading, and time-varying nature of wireless channels (Cabric et al., 2004). Due to the severe multipath fading, a CR user may fail to detect the presence or the absence of the PU. The performance of a single CR user using conventional energy detector (CED) has been studied in several fading channels such as log-normal shadowing, Rayleigh, and Nakagami-$m$ fading channels in Nallagonda et al. (2012a) and Digham et al. (2003) where the Nakagami distribution provides flexibility in describing the fading severity of the channel and considers special cases such as the well known Rayleigh fading for a certain value of the fading parameter ($m = 1$). Cooperative spectrum sensing (CSS) improves the detection performance where all CR users use identical CEDs and sense the PU via faded sensing (S) channels individually and send their sensing information in the form of 1-bit binary decisions (1 or 0) via ideal (noiseless) reporting (R) channels to fusion center (FC) Ghasemi and Sousa (2005, 2007) and Nallagonda et al. (2012b). Then, the FC employs any one of the hard decision combining fusion rules such as OR-logic, AND-logic and majority-logic fusion rules and makes a global decision about the presence or the absence of the PU. In (Quan, 2008; Ma and Li, 2007), soft decision combining fusion for cooperative sensing based on energy detection has been studied. In the case of soft decision, CR users forward the entire sensing data i.e., received energies at individual CR users to the FC without performing any local decision (1 or 0) at each CR user.

It should be noted that the channels between the PU and CR users are called sensing channels (S-channels) and the channels between the CRs and the FC are called reporting channels (R-channels). The performance of CED based CSS has also been studied in several fading channels where R-channels are assumed to be ideal (noiseless) and S-channels are considered as Hoyt (or Nakagami-$q$) Nallagonda et al., 2012c, Rican (or Nakagami-$n$) and Weibull fading channels. Hoyt distribution (Hoyt, 1947; Chandra et al., 2013; Simon and Alouini, 2004), also known as Nakagami-$q$ distribution ($q$ being the fading severity parameter), allows us to span the range of fading distribution from one-sided Gaussian ($q = 0$) to Rayleigh fading ($q = 1$), and is used extensively for modeling more severe than Rayleigh fading wireless links. The Weibull distribution also provides flexibility in describing the fading severity of the channel and considers special cases such as the well known Rayleigh fading for a certain value of the fading parameter (Ismail and Matalgah, 2006). The performance of single CR user based spectrum sensing (Nallagonda et al., 2011) is the best in Weibull fading channel among other channels such as Rician, Nakagami-$m$. Depending on the particular propagation environment (either in sensing side or reporting side) and the underlying communication scenario, several such models have been investigated. Table 1 lists the fading models along with their application environments.

**Table 1** Type of fading and Propagation environment (Chandra, 2011; Hashemi, 1993; Adawi et al., 1988).

| Fading | Propagation environment |
|---|---|
| Rayleigh | Mobile systems with no line-of-sight (LoS) path, propagation of reflected and refracted paths through troposphere and ionosphere, maritime ship-to-ship communication links |
| Rician | LOS paths of microcellular urban and suburban land mobile, picocellular indoor, and factory environments, dominant LOS path of satellite radio links |
| Hoyt | Satellite links subject to strong ionospheric scintillation |
| Weibull | Good fit to mobile radio fading data, indoor, and outdoor environments |

However, in many practical situations R-channels may not be noiseless channels. More precisely, the wireless links between CRs and FC my experience noise and fading or shadowed. Several researchers assume that CRs report their local decisions or energy values to FC via noisy and faded channels. Particularly, in Zhao et al., 2013, both sensing and reporting channels are assumed as noisy and faded. With this assumption, the author proposed filter-bank based soft decision fusion (SDF) cooperative spectrum sensing system. In Zou et al., 2011, a selective-relay based cooperative spectrum sensing scheme, assuming noisy and Rayleigh faded channels in both sensing and reporting sides, is proposed. The R-channels are considered as noisy and Rayleigh faded in Ferrari and Pagliari (2006), Chen et al., 2004, in the context of a sensor network where sensors report their decisions to FC. The performance of CSS can be improved further by utilizing an improved energy detector (IED) at each CR user, where the conventional energy detector is modified by replacing the squaring operation of the received signal amplitude with an arbitrary positive power parameter (Chen, 2010; Singh et al., 2011). The performance of CSS using IED and SC based multi antenna at each CR is analysed (Singh et al., 2012) where S-channel is considered as Rayleigh faded and R-channel is considered as binary symmetric channel (BSC) only with a fixed error probability of '$r$'. However, impact of different types of fading in R-channels is not considered. In Nallagonda et al., 2012d, two cases of fading such as: (i) Rayleigh and (ii) Nakagami-$m$ with noise are only considered in R-channel to evaluate the performance of same network as given in Singh et al. (2012).

In the present paper we consider the same detection scheme at CR level as presented in Singh et al. (2012) and Nallagonda et al. (2012d) and extend the analysis to considering three other cases of fading in the R-channel such as Hoyt, Rician, and Weibull in contrast to a simple BSC as discussed in Singh et al. (2012) and well known fading channels as discussed in Nallagonda et al. (2012d). The motivation behind considering Hoyt (Subadar and Sahu, 2011), Rician (Khatalin and Fonseka, 2006) and Weibull (Ikki and Aissa, 2011; Ivan et al., 2011) is that they represent the most general fading situations. In this paper first we derive an expression for probability of false alarm and also expressions for probability of missed detection in non-faded (AWGN) and Rayleigh faded sensing environments in terms of cumulative distribution function (CDF) using Van Trees, 1968, Eq. (41), chapter 2. It should be noted in this paper that the expressions for probability of false alarm and probability of missed detection via CDF involves multi-antenna parameter ($M$) in CDF only. More precisely, in this paper we consider a Rayleigh faded S-channel, and cases with several types of fading such as Hoyt, Rayleigh, Rician, and Weibull in R-channels. Missed detection and total error probabilities are selected as the key performance metric